Search for the SM Higgs boson in the decay channel $H \rightarrow ZZ^{(*)}$ in ATLAS

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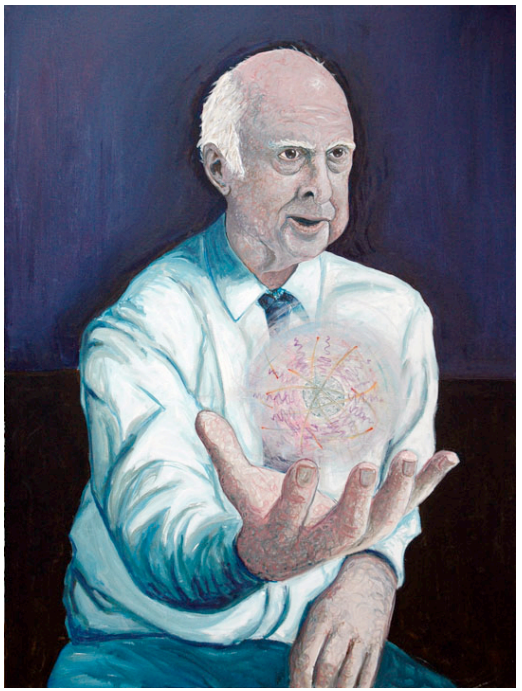
on behalf of the ATLAS collaboration

CERN

Hadron Collider Physics
Kyoto November 14th 2012



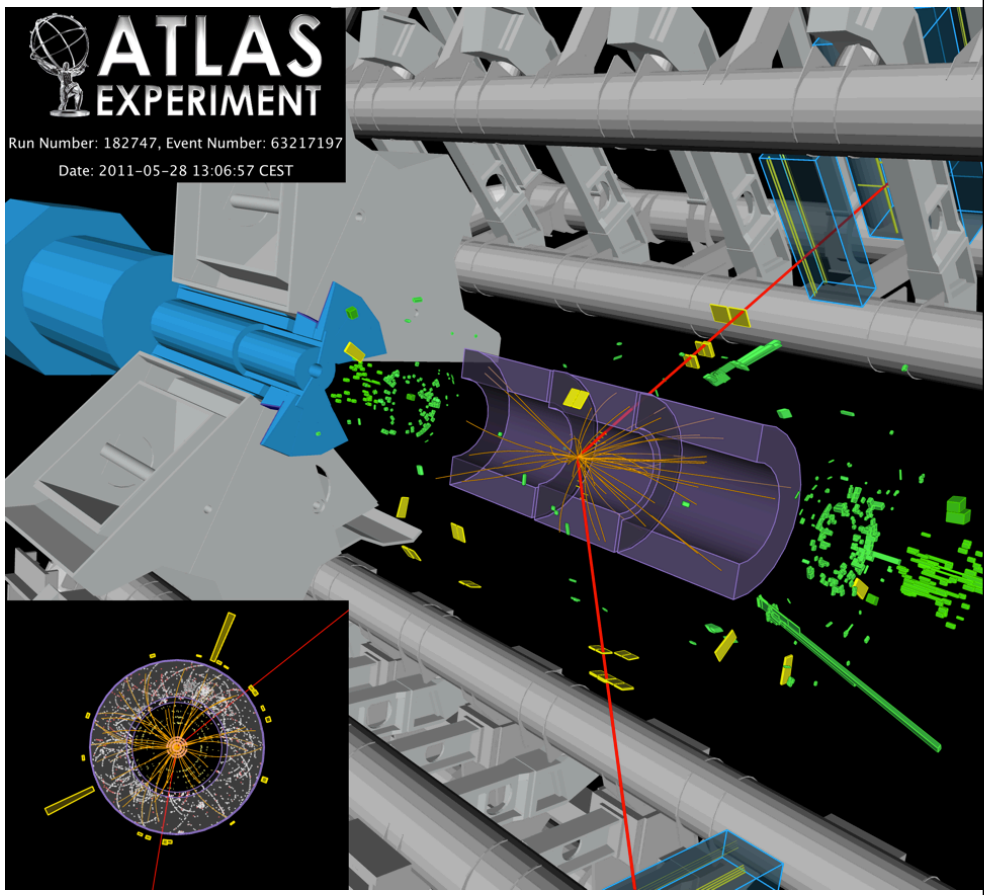
Introduction

- Signature: $H \rightarrow ZZ^{(*)} \rightarrow 4l$ (l = e, μ)
- The "golden channel":
  - Small rates, but high S/B
  - Can be fully reconstructed; mass resolution ~2% at 130 GeV
- Cross section times branching ratio (at m_H=125 GeV):
  - ~ 2.2 fb at $\sqrt{s}$=7 TeV
  - ~ 2.8 fb at $\sqrt{s}$=8 TeV
- Backgrounds:
  - Irreducible: $pp \rightarrow ZZ^{(*)} \rightarrow 4l$
  - Reducible: Z+jets, $Z\bar{b}\bar{b}$, $\bar{t}\bar{t}$ (sizeable at low Higgs masses)
- Mass range under consideration: 110 GeV to 600 GeV
- Four final states: 4e, 4μ, 2e2μ, 2μ2e
- Data sets used:
  - 7 TeV : 4.8 fb^{-1}
  - 8 TeV : 5.8 fb^{-1}

Event Selection

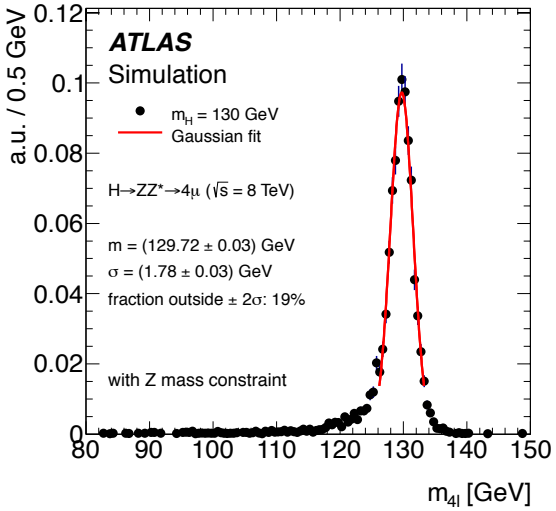
- **Two same-flavour opposite-sign di-leptons (e/μ)**

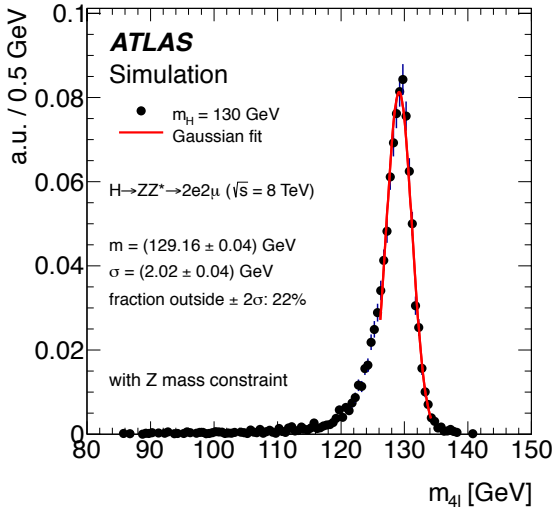
- Optimised phase space to enhance low mass sensitivity
  - $p_T^{l,2,3,4}$ > 20,15, 10, 7 GeV (6 GeV for μ)
  - Leading di-lepton mass : 50 < m_{12} < 106GeV
  - Sub-leading di-lepton mass :
    - m_{thr} (m_{4l}) < m_{34} < 115 GeV ;m_{thr} = 17.5 - 50 GeV
  - all same-flavour opposite-sign pairs m_{ll}>5 GeV
  - ΔR(l,l′) > 0.10(0.20) for all same(different)-flavour
- Additional requirements to reduce background
  - Calorimeter isolation
  - Track isolation
  - Impact parameter significance
- Z mass constraint of leading Z

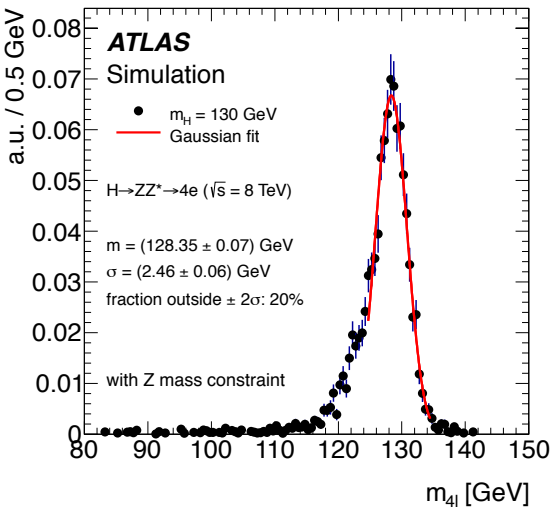


Mass Resolution

- Typical search for narrow peak on top of smooth background
  - Resolution crucial for sensitivity!
  - Final states separated in 4μ, 2μ2e, 2e2μ & 4e
- ATLAS detector provides excellent resolution!
  - Relative resolution of 1.6 - 2.1% for m_H=130 GeV
  - Further improved by using m_Z constrained fit
  - Relative resolution of 1.4 - 1.9% for m_H=130 GeV

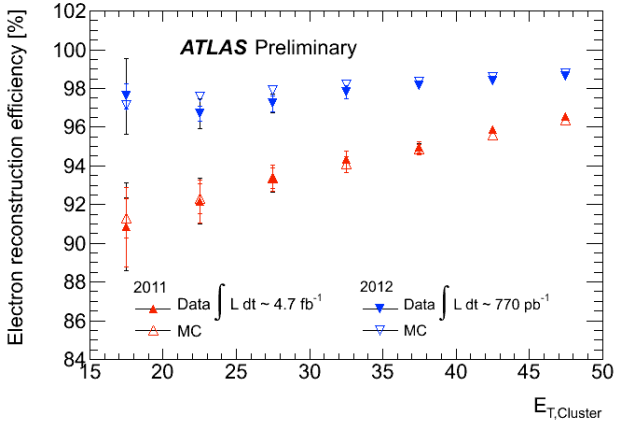


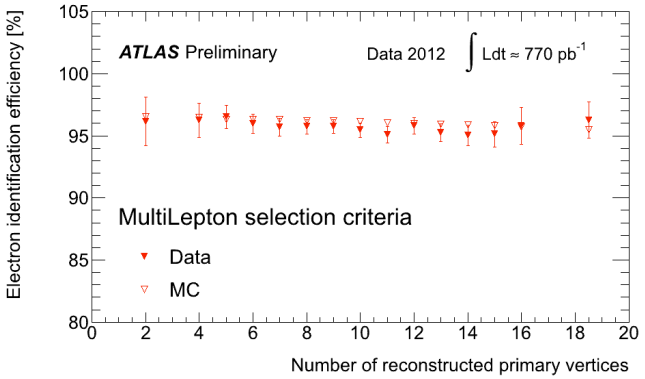


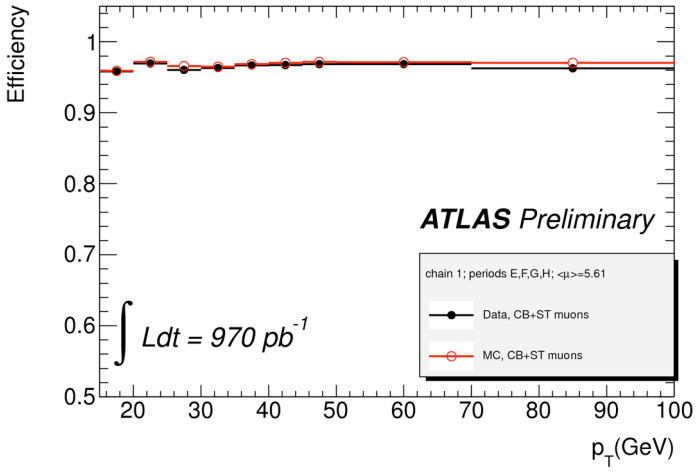


Lepton Reconstruction and Performance

- Electrons in 2012 data
  - Improved electron reconstruction
    - New track finding/track-fit
  - Improved electron identification
    - Pile-up robust
    - Higher rejection and efficiency with respect to 2011 data
  - Pile-up robust calorimeter-based isolation

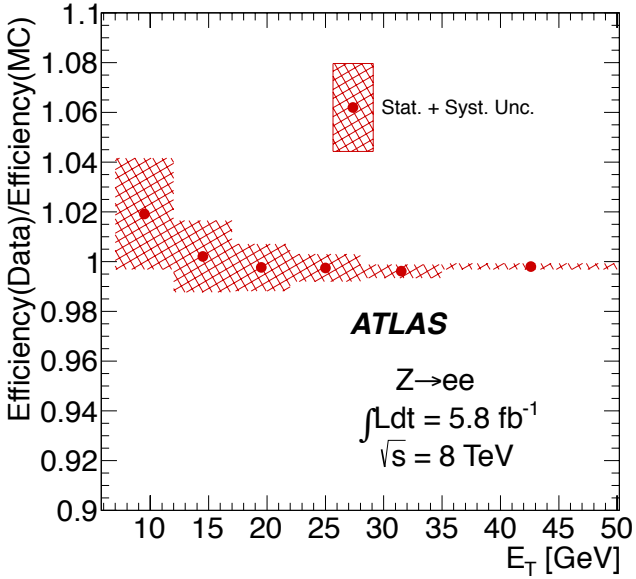


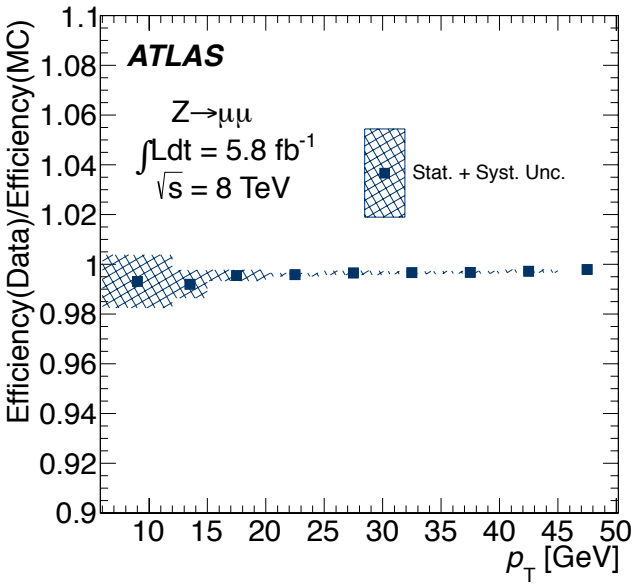




- Muons
  - Combining/Matching Inner Detector (ID) tracks with complete or partial tracks in Muon Spectrometer (MS)
  - Extend muon coverage:
    - ID-track + energy deposit profile in calorimeter ($|\eta|<0.1$/ $p_T>15$ GeV)
    - MS stand-alone ($2.5<|\eta|<2.7$)

Event Selection Performance



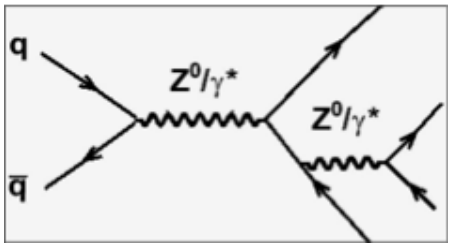


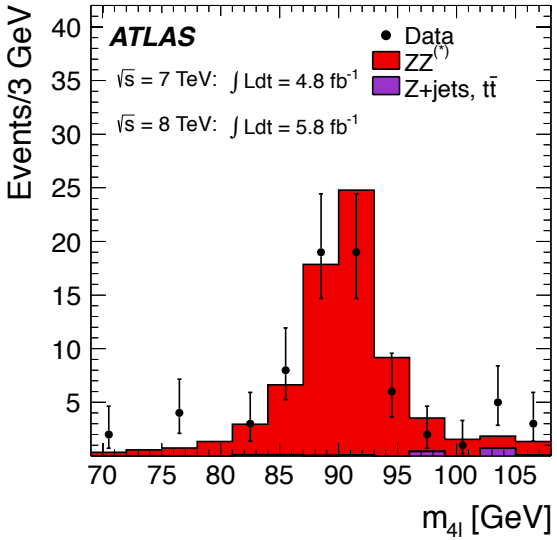
Isolation & IP requirements performance controlled from data

- Signal-like leptons:
  - $Z \rightarrow ll$ tag-and-probe
- Background-like leptons:
  - Z+'μ'and Z+'e'

$pp \rightarrow Z \rightarrow 4l$

- Relax analysis requirements: m_{12}>30 GeV, m_{34}>5 GeV and lower p_T for muons (>4 GeV)
  - Cross-check of analysis configuration
  - Indicates reasonable behaviour of lepton reconstruction/ identification

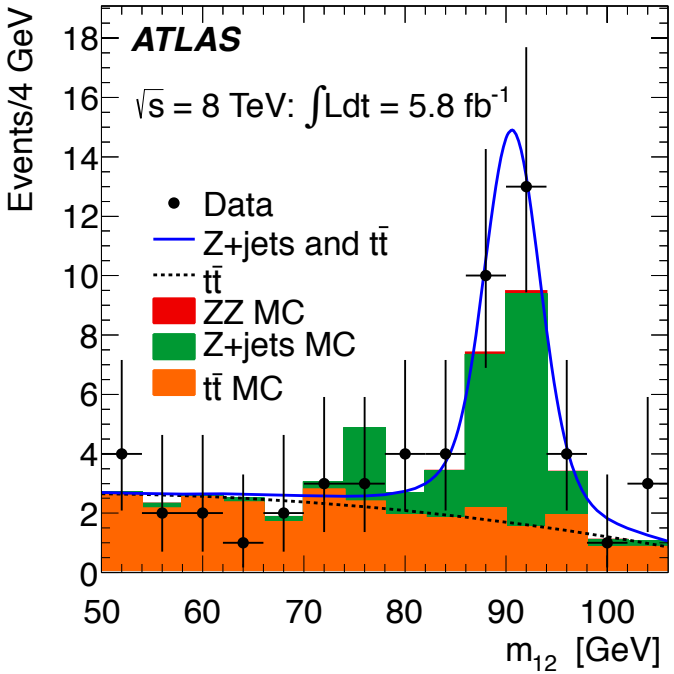




Background Estimates: ll+μμ

m_{12} fit

- Sub-leading di-muon
  - Remove isolation requirement
  - Fail IP significance requirement (removes ZZ)
- m_{12} spectrum: $Zb\bar{b}/t\bar{t}$ contributions clearly separated
- Obtain yields by fit of the two components
- Extrapolate to Signal Region
  - Transfer factors from MC
  - Cross-checked with data



$e^{\pm}\mu^{\mp}+\mu^{\pm}\mu^{\mp}$

- $e^{\pm}\mu^{\mp}$ leading di-lepton with $Z \rightarrow ll$ veto $\rightarrow t\bar{t}$ dominated
- Observed 16 (8) events compared to 18.9±1.1 (11.0 ± 0.6) expected in 8 (7) TeV
- Extrapolation to signal region → compatible results with m_{12} fit

Background Estimates: ll+ee

- Main contribution: Z+jets
  - Hadrons mis-identified as electrons (f)
  - Electrons from photon conversions (c/γ)
  - Electrons from semi-leptonic decays of heavy flavour (Q)
- Background composition crucial to extrapolate to Signal Region

	$4e$		$2\mu 2e$	
	Data	MC	Data	MC
EE	32	22.7±4.8	31	24.9±5.0
EC	6	6.0±2.5	2	1.9±1.4
EF	18	19.0±4.4	26	15.3±3.9
CE	4	8.8±3.0	6	5.1±2.3
CC	1	5.3±2.3	6	4.2±2.0
CF	12	8.8±3.0	15	15.3±3.9
FE	16	5.7±2.4	12	8.4±2.9
FC	6	6.5±2.6	7	4.3±2.1
FF	12	17.4±4.2	16	33.6±5.8
Total	107	100±10	121	113±11

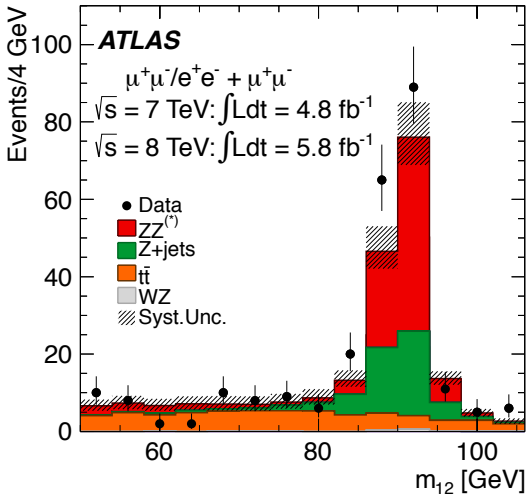
Base-line method

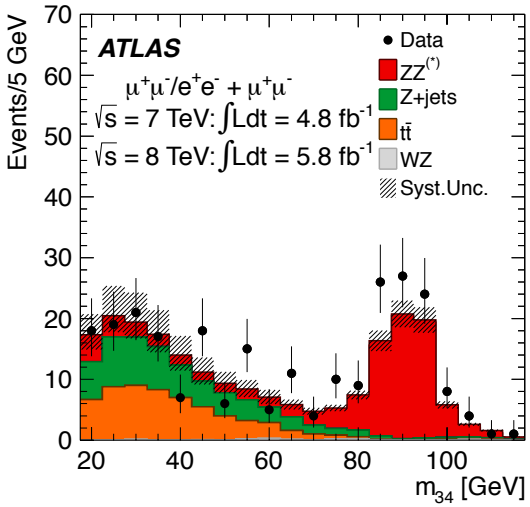
- Relax identification in sub-leading di-electron
- Use the detector to ascertain the composition
  - Transition Radiation (f/em)
  - Number of B-layer hits (c/γ)
  - Fraction of energy in first sampling of e/m calorimeter (f/em)
  - Lateral containment of cluster along φ in 2nd e/m sampling (f/em)
  - Allows for a check of the MC composition
- Extrapolate yields in each category to the signal region using MC

Alternative method in Same-Charge sub-leading di-electron

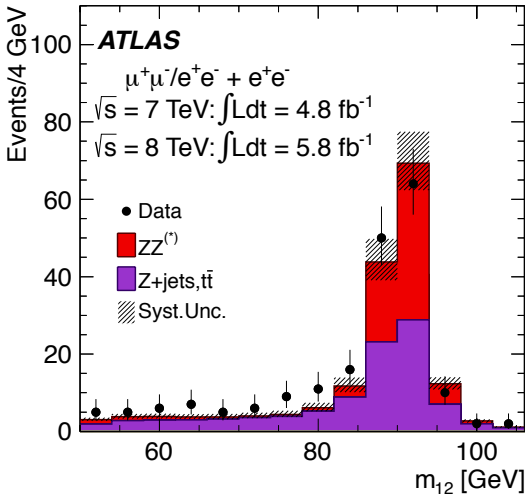
- Relax requirements on softest electron
- Composition from fit (separate Conversions/Hadrons)

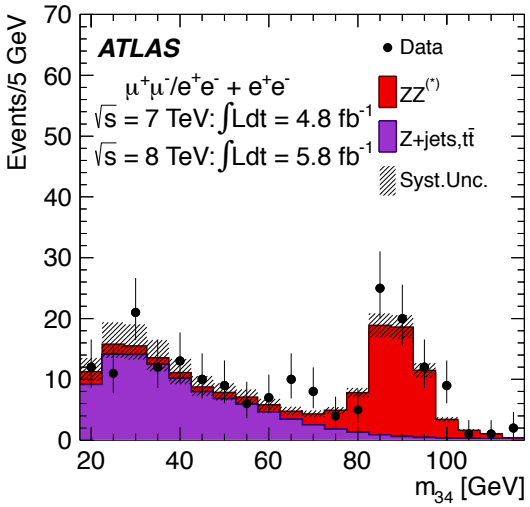
Background Estimates: Control Regions





- Select a background-dominated control region
  - Remove isolation/impact parameter requirements on sub-leading di-lepton
- Normalisation taken from data-driven estimates
- Normalization/shape of reducible backgrounds well described





Reducible Background Estimates: Summary

8 TeV

Method	Estimated nr. of events
4μ	
m_{12} fit: Z + jets contribution	$0.51\pm 0.13 \pm 0.16^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.044\pm 0.015\pm 0.015^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.058\pm 0.015\pm 0.019$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.41\pm 0.10 \pm 0.13^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.040\pm 0.013\pm 0.013^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.051\pm 0.013\pm 0.017$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$4.9\pm 0.8 \pm 0.7^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$4.1\pm 0.6 \pm 0.8$
$3\ell + \ell$ (same-sign)	$3.5\pm 0.5 \pm 0.5$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.9\pm 0.7 \pm 0.8^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.1\pm 0.5 \pm 0.6$
$3\ell + \ell$ (same-sign)	$3.0\pm 0.4 \pm 0.4$

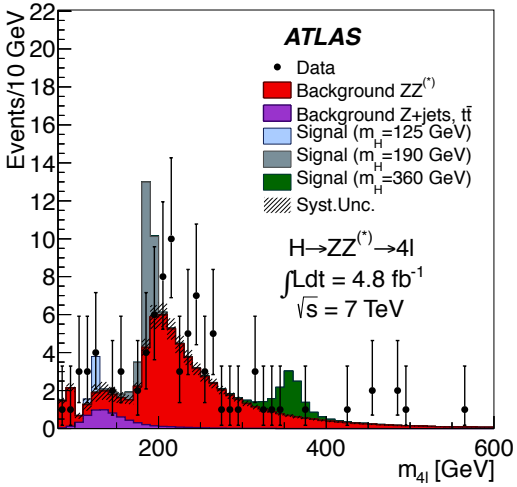
7 TeV

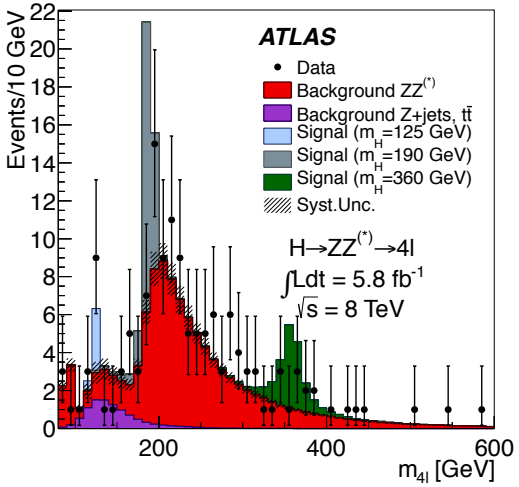
Method	Estimated nr. of events
4μ	
m_{12} fit: Z + jets contribution	$0.25\pm 0.10 \pm 0.08^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.022\pm 0.010\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.025\pm 0.009\pm 0.014$
$2e2\mu$	
m_{12} fit: Z + jets contribution	$0.20\pm 0.08 \pm 0.06^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.020\pm 0.009\pm 0.011^{\dagger}$
$t\bar{t}$ from $e^{\pm}\mu^{\mp} + \mu^{\pm}\mu^{\mp}$	$0.024\pm 0.009\pm 0.014$
$2\mu 2e$	
$\ell\ell + e^{\pm}e^{\mp}$	$2.6\pm 0.4 \pm 0.4^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.7\pm 0.9 \pm 0.6$
$3\ell + \ell$ (same-sign)	$2.0\pm 0.5 \pm 0.3$
$4e$	
$\ell\ell + e^{\pm}e^{\mp}$	$3.1\pm 0.6 \pm 0.5^{\dagger}$
$\ell\ell + e^{\pm}e^{\pm}$	$3.2\pm 0.6 \pm 0.5$
$3\ell + \ell$ (same-sign)	$2.2\pm 0.5 \pm 0.3$

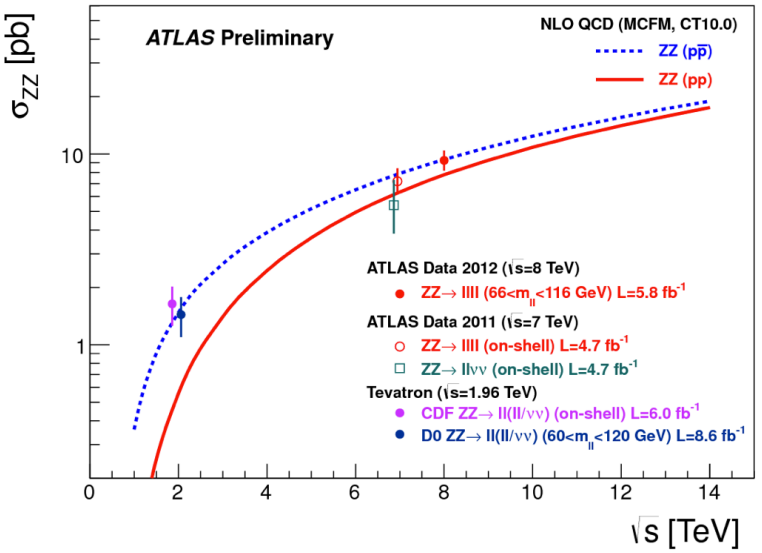
value ± stat ± syst

- Multiple methods are used which yield compatible results
  - The "†" symbol indicates the method used for the nominal normalisation

Results

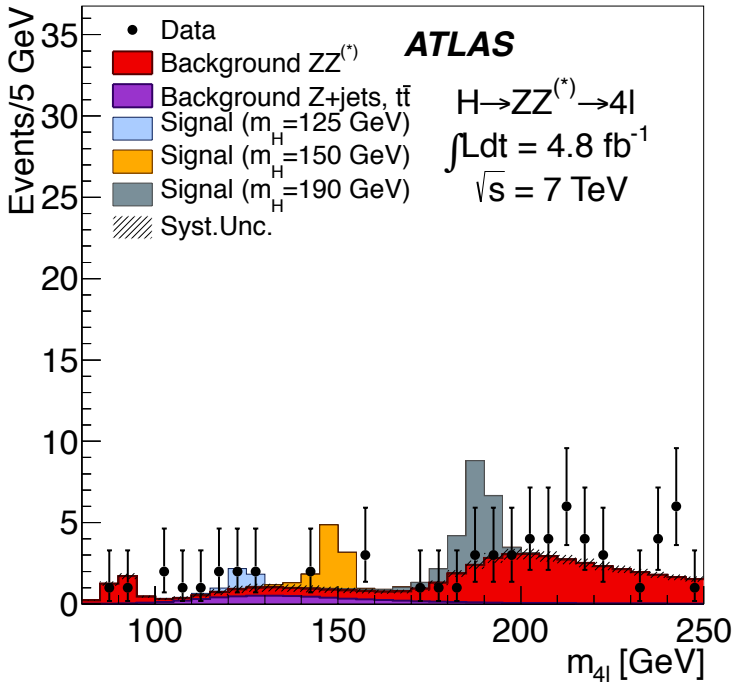


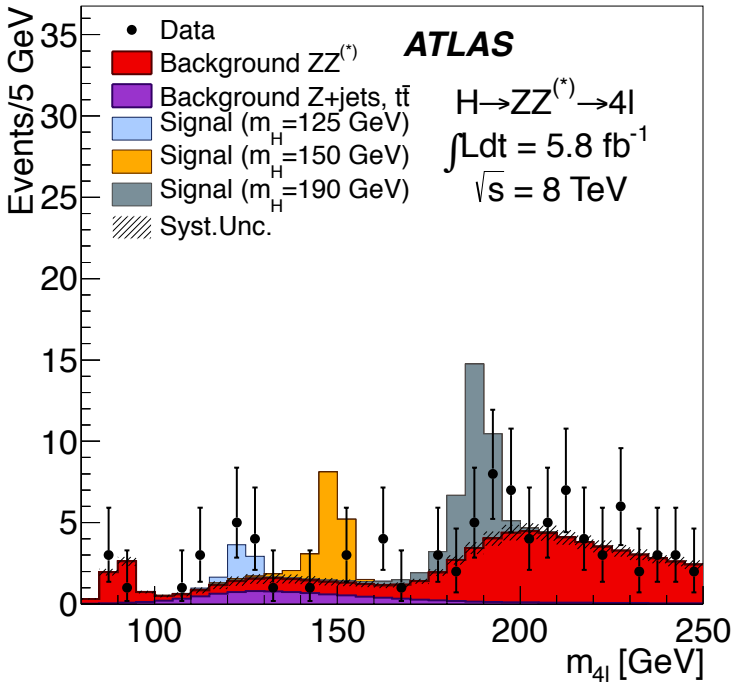




- Observed events in the range 80 < m_{4l} < 600 GeV for 7 and 8 TeV
- For m_{4l}>160 GeV:
  - Observe slightly more events than expected for 2011 and 2012
  - Events have the expected characteristics for ZZ→4l production
  - Reflected in the ATLAS ZZ production cross-section measurement

Results





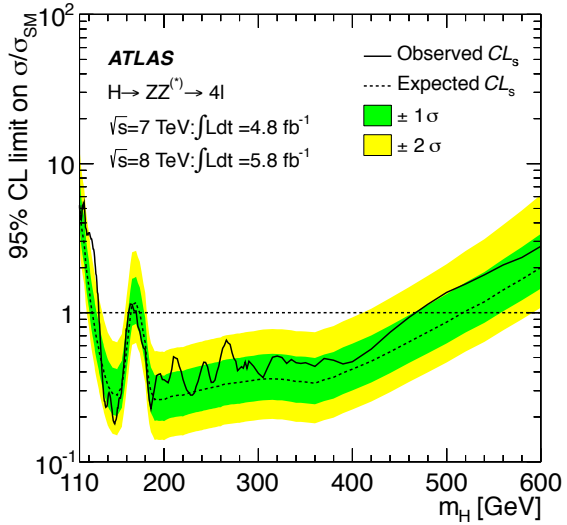
Events in m_{4l} 125±5 GeV window

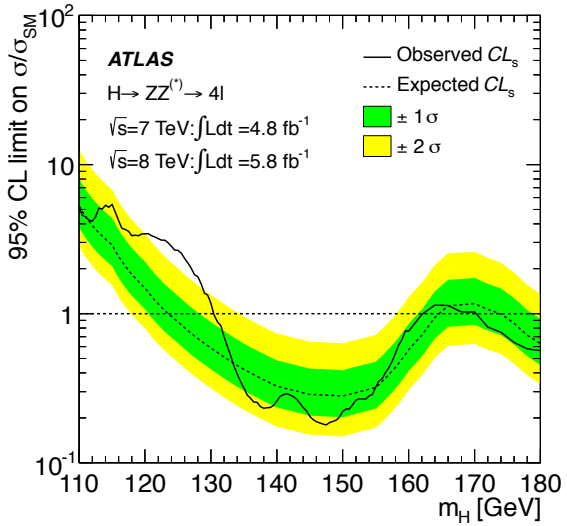
	Signal	$ZZ^{(*)}$	Z + jets, $t\bar{t}$	Observed
4μ	2.09±0.30	1.12±0.05	0.13±0.04	6
$2e2\mu/2\mu2e$	2.29± 0.33	0.80±0.05	1.27±0.19	5
$4e$	0.90±0.14	0.44±0.04	1.09±0.20	2

Expected S/B (m_H=125 GeV)

- 4μ ~ 1.7
- 2e2μ/2μ2e ~ 1.1
- 4e ~ 0.6

Exclusion Limits

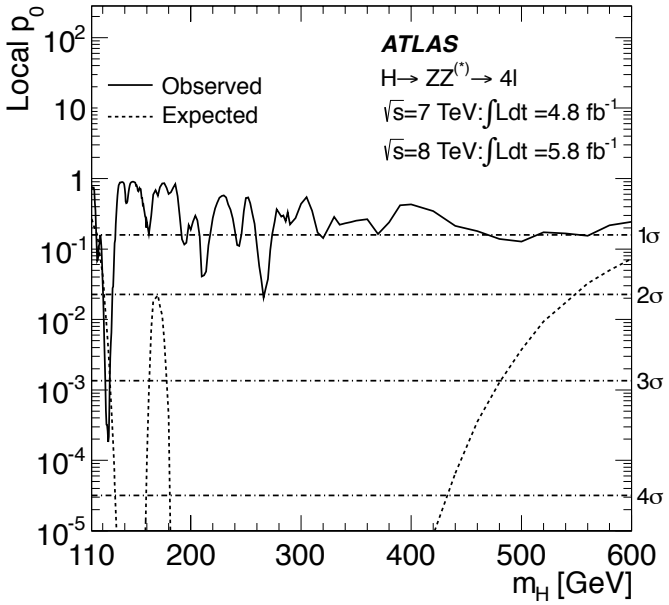


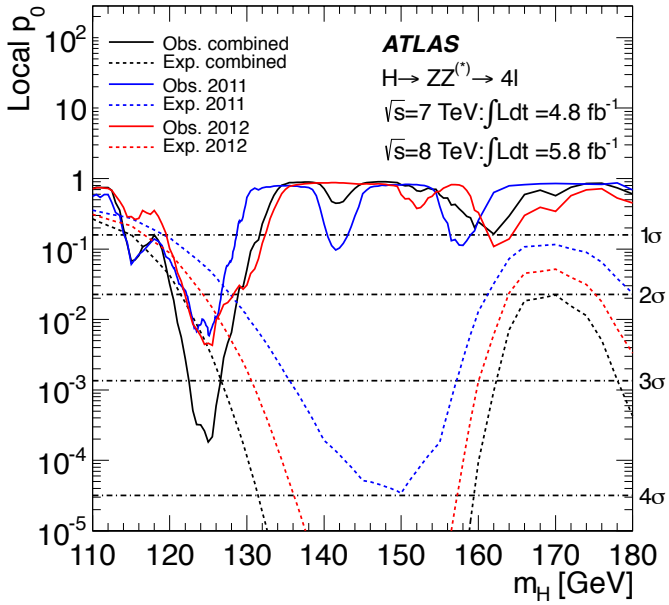


Statistics Treatment:
• profile likelihood ratio [Eur.Phys.J.C71:1554,2011] nuisance parameters for systematic uncertainties
• exclusion limits using CL_S [J. Phys. G 28 (2002) 2693-2704]

- Exclusion limits using CL_S, profile likelihood ratio
  - Exclusion: Expected: 124-164 and 176-500 [GeV]
- Observed: 131-162 and 170-460 [GeV]
  - Much weaker than expected at 120-130 GeV

Significance of Excesses



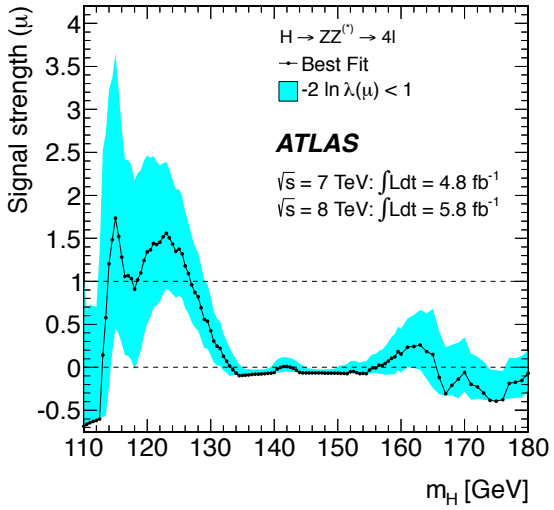


- At high m_H, small fluctuations from background
- At low m_H, consistent excesses in 2011 and 2012
  - Combined: 3.6σ @ 125 GeV
  - (expected significance 2.7σ)

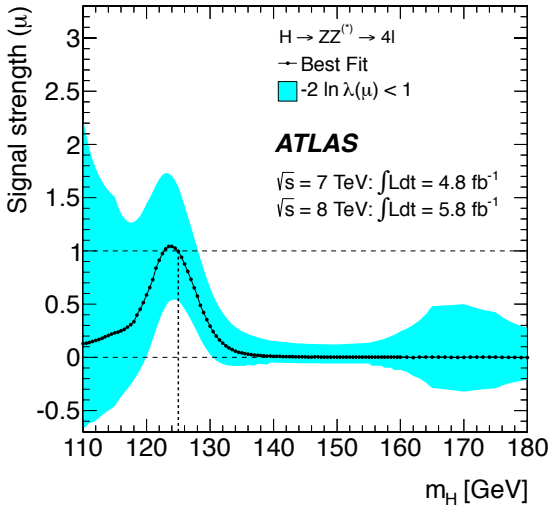
Signal Strength

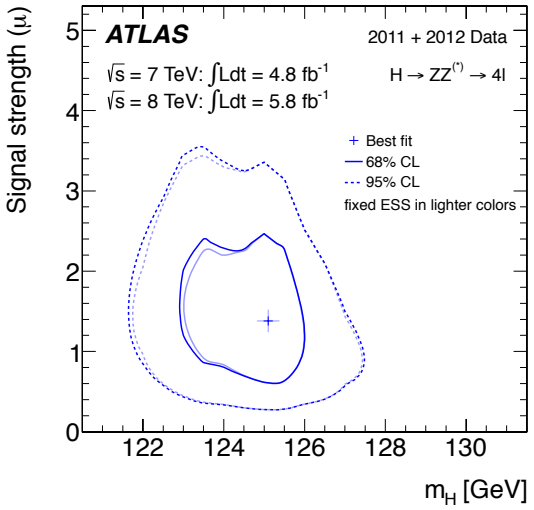
- μ = (best fit signal rate at m_H)/(expected SM rate at m_H)
- Best fit value at m_H=125 GeV (lowest p0): 1.4 ± 0.6

Data



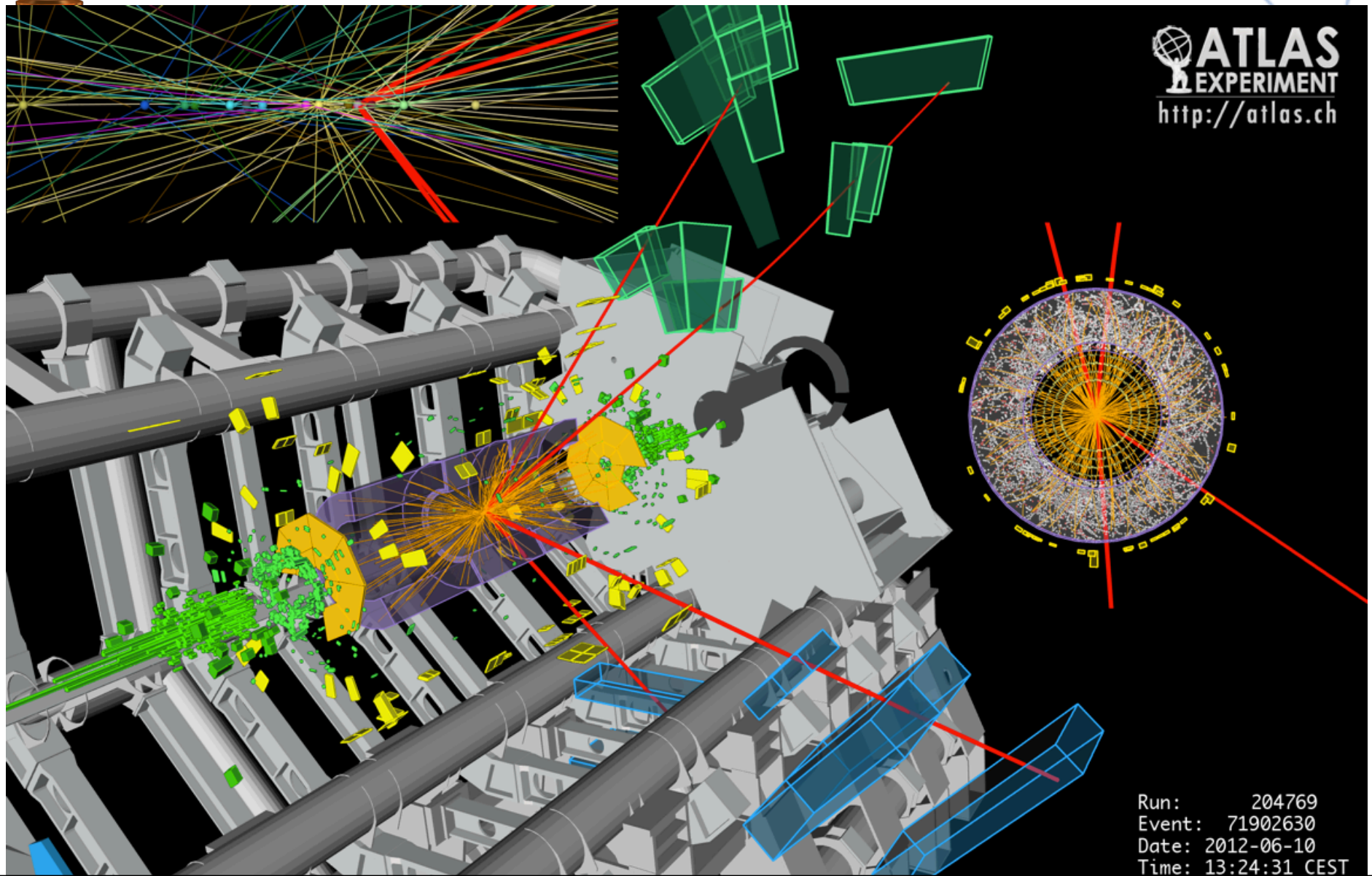
Signal Injection





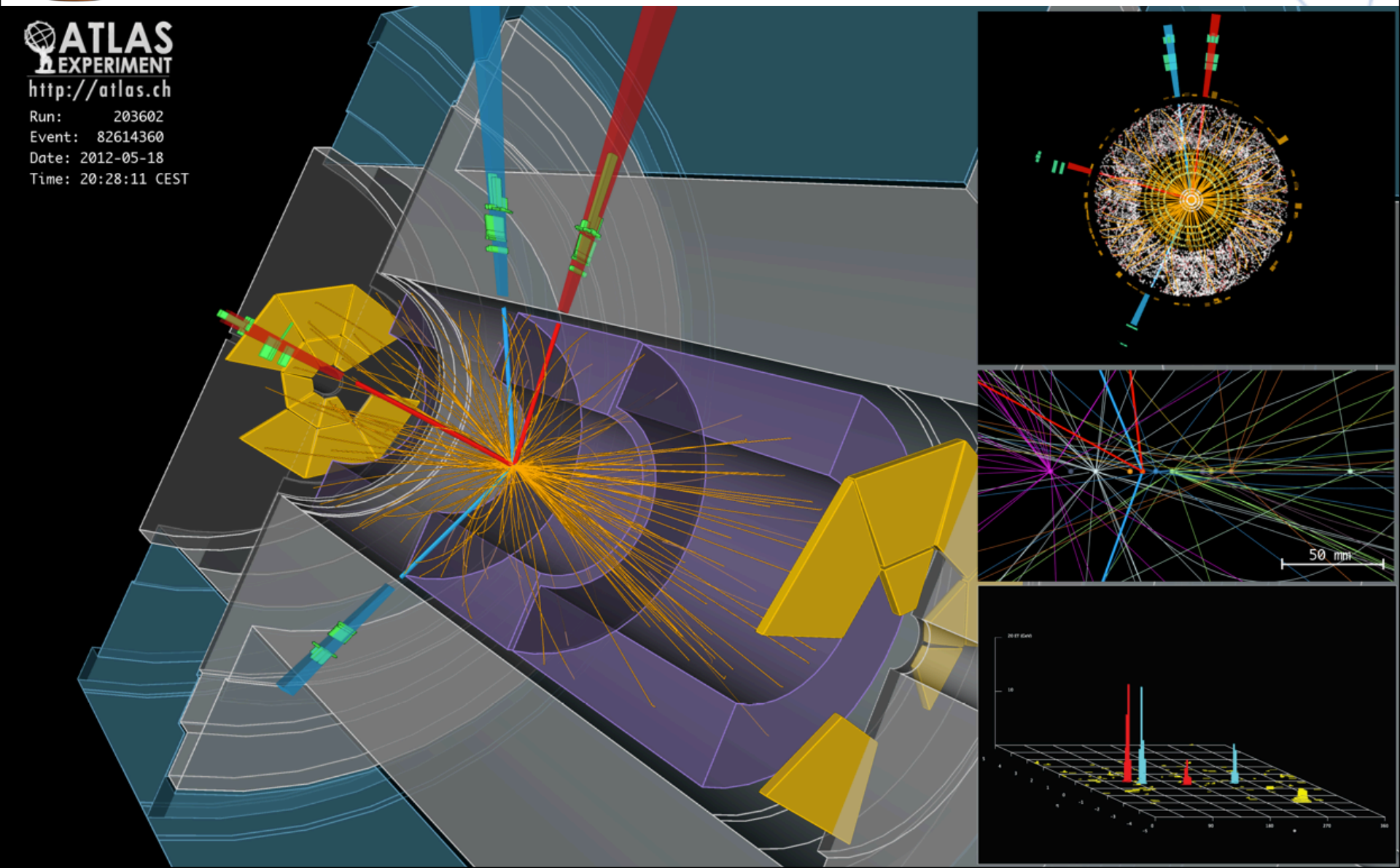
$m_{4\mu}$ = 125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7 [GeV]
m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices!

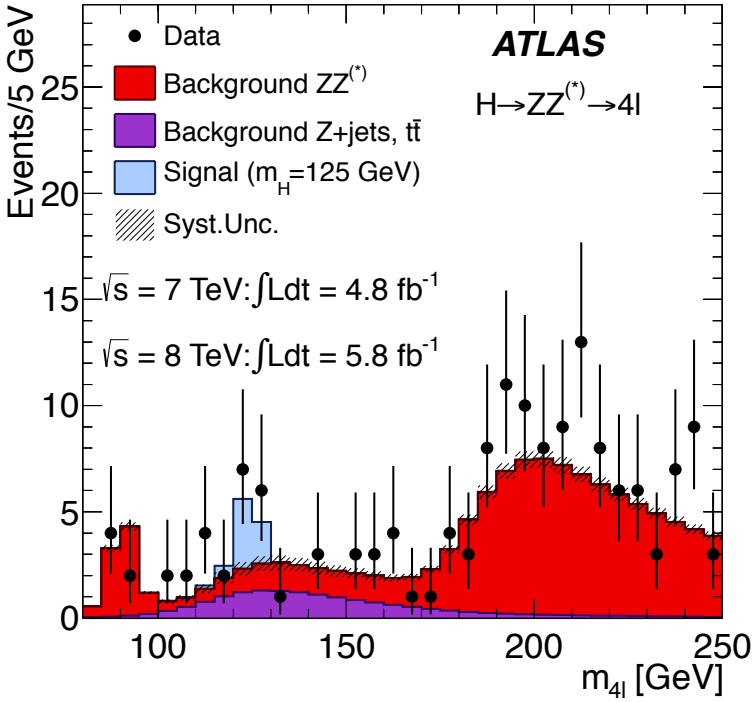


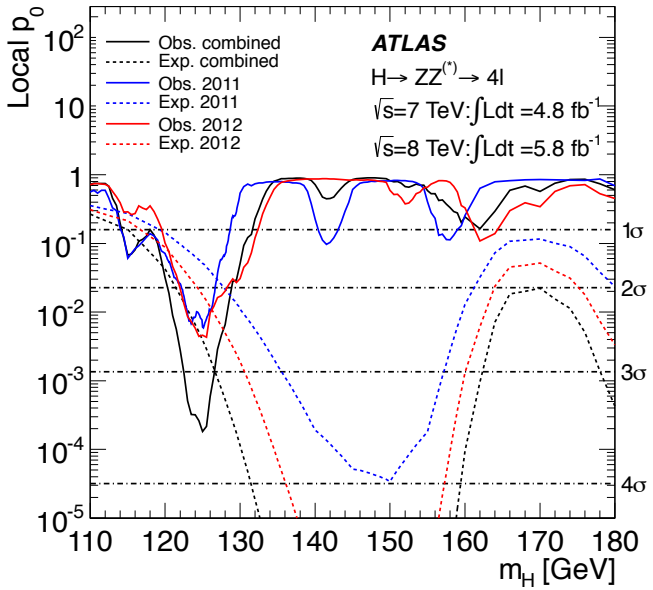
m_{4e} = 124.6 GeV

p_T (electrons)= 24.9, 53.9, 61.9, 17.8 [GeV]
m_{12}= 70.6 GeV, m_{34}= 44.7 GeV
12 reconstructed vertices!



Summary



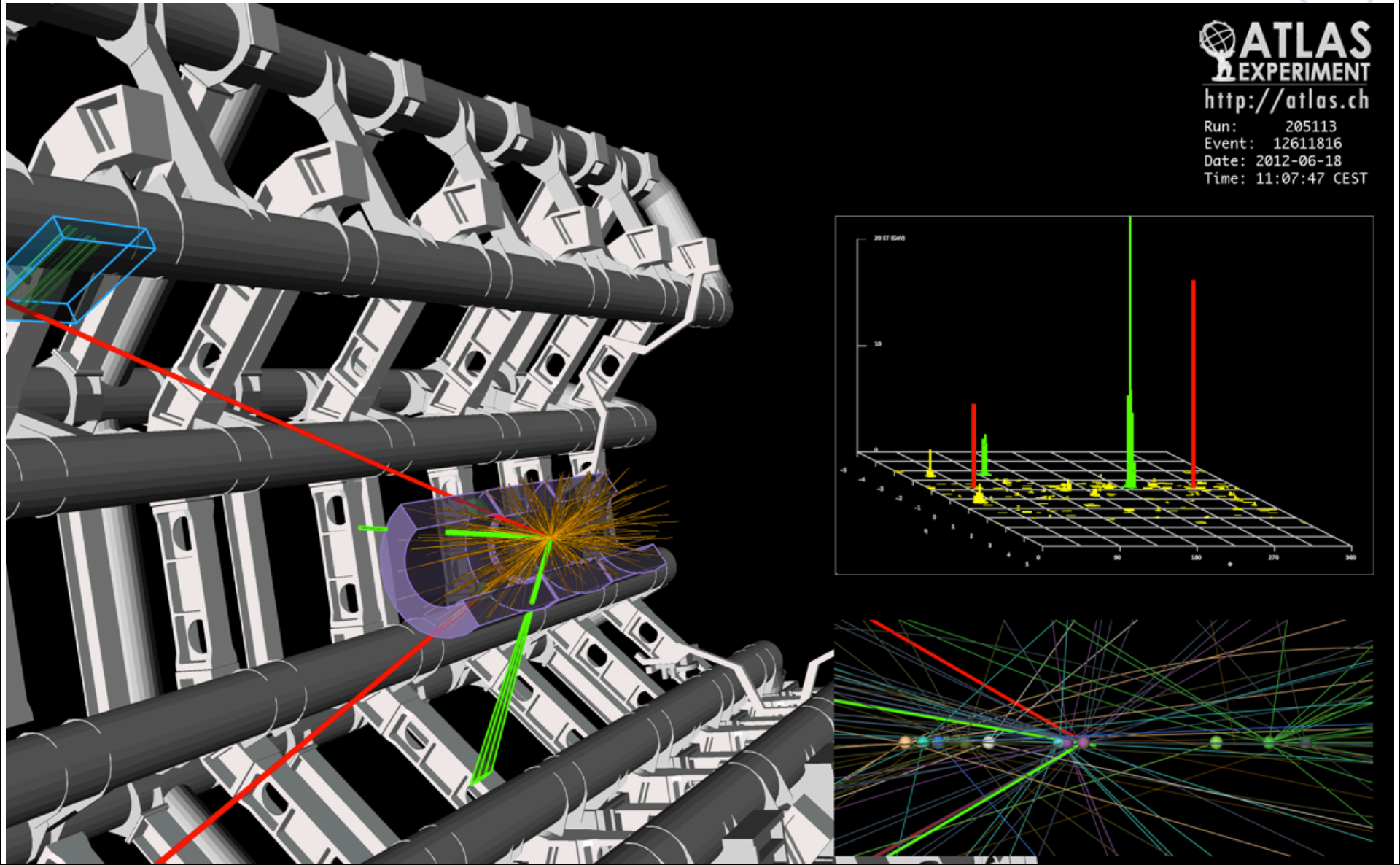


- Great progress has been made to improve on:
  - Lepton performance and pile-up robustness
- Sensitivity for the low m_H region
  - Robust background estimation methods
  - multiple methods per background
- The ATLAS $H \rightarrow ZZ^{(*)} \rightarrow 4l$ search, observed an excess of events over the background only hypothesis at $m_H \sim 125$ GeV
  - Consistent in both 2011 and 2012 datasets.
  - Combining datasets, 3.6σ local significance (expected significance 2.7σ)
  - Signal strength fit value at m_H=125 GeV (lowest p0): $\mu = 1.4 \pm 0.6$
- Will update to the full 2012 dataset and combine in the future as well as extend the analysis to measure the particles properties.

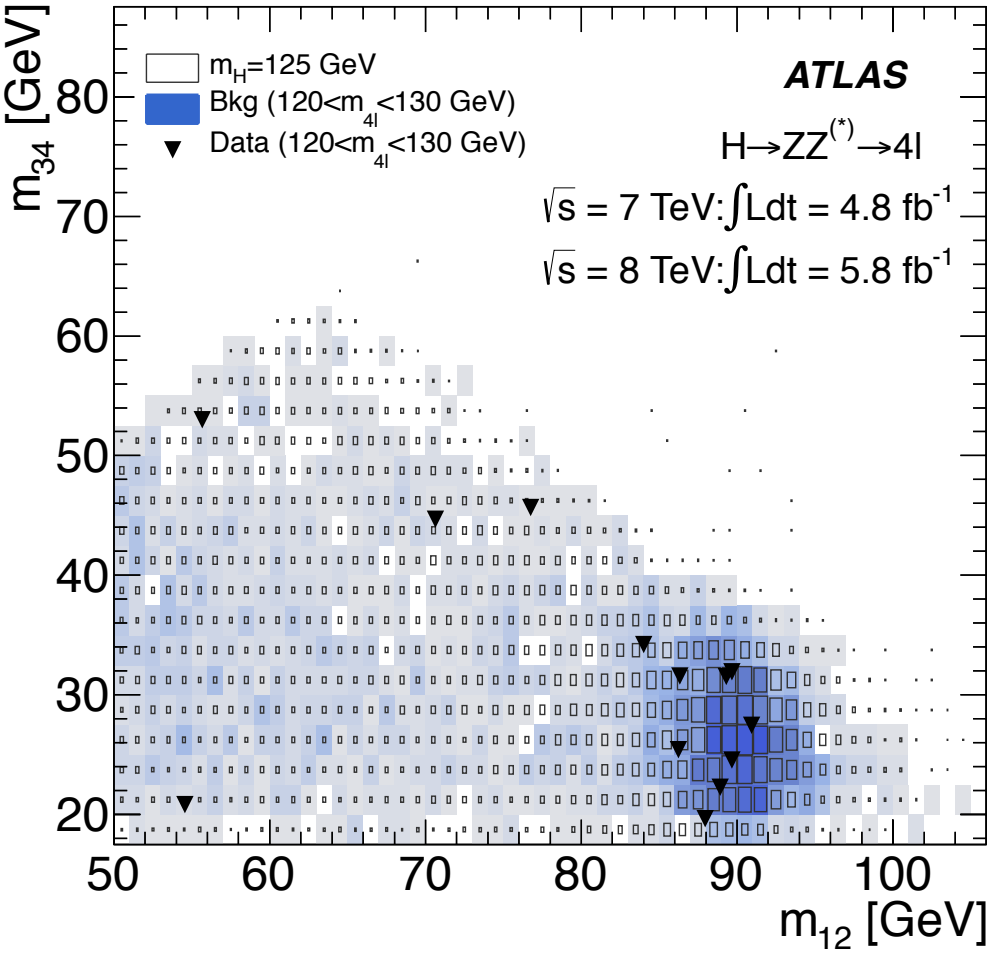
Extras

$m_{2e2\mu}$ = 123.9 GeV

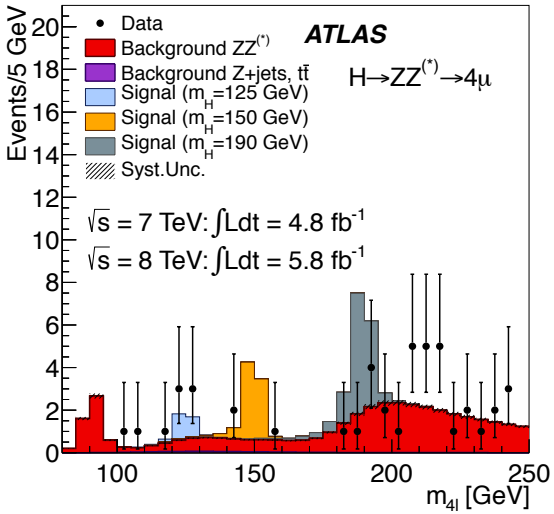
p_T ($ee\mu\mu$)= 18.7, 76, 19.6, 7.9 [GeV]
m_{ee}= 87.9 GeV, $m_{\mu\mu}$= 19.6 GeV
12 reconstructed vertices

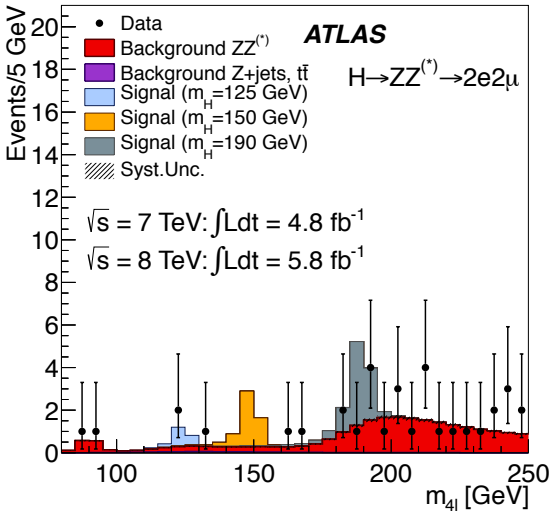


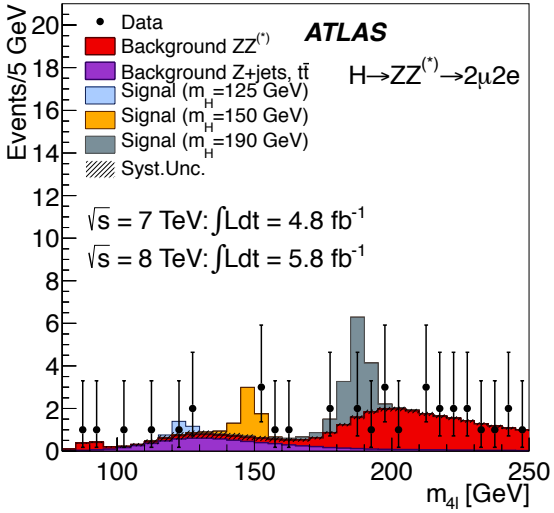
m_{12} vs m_{34}

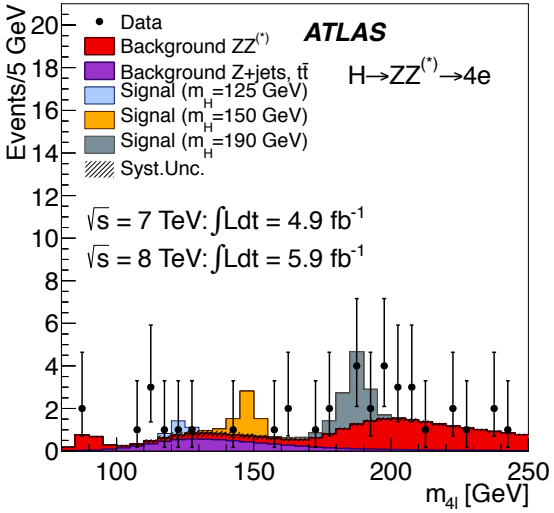

m_H=125 GeV
Bkg (120<m_{4l}<130 GeV)
Data (120<m_{4l}<130 GeV)
ATLAS
$H \to ZZ^{(*)} \to 4l$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8 fb^{-1}
m_{34} [GeV]
m_{12} [GeV]
20
30
40
50
60
70
80
50
60
70
80
90
100

Per channel break down

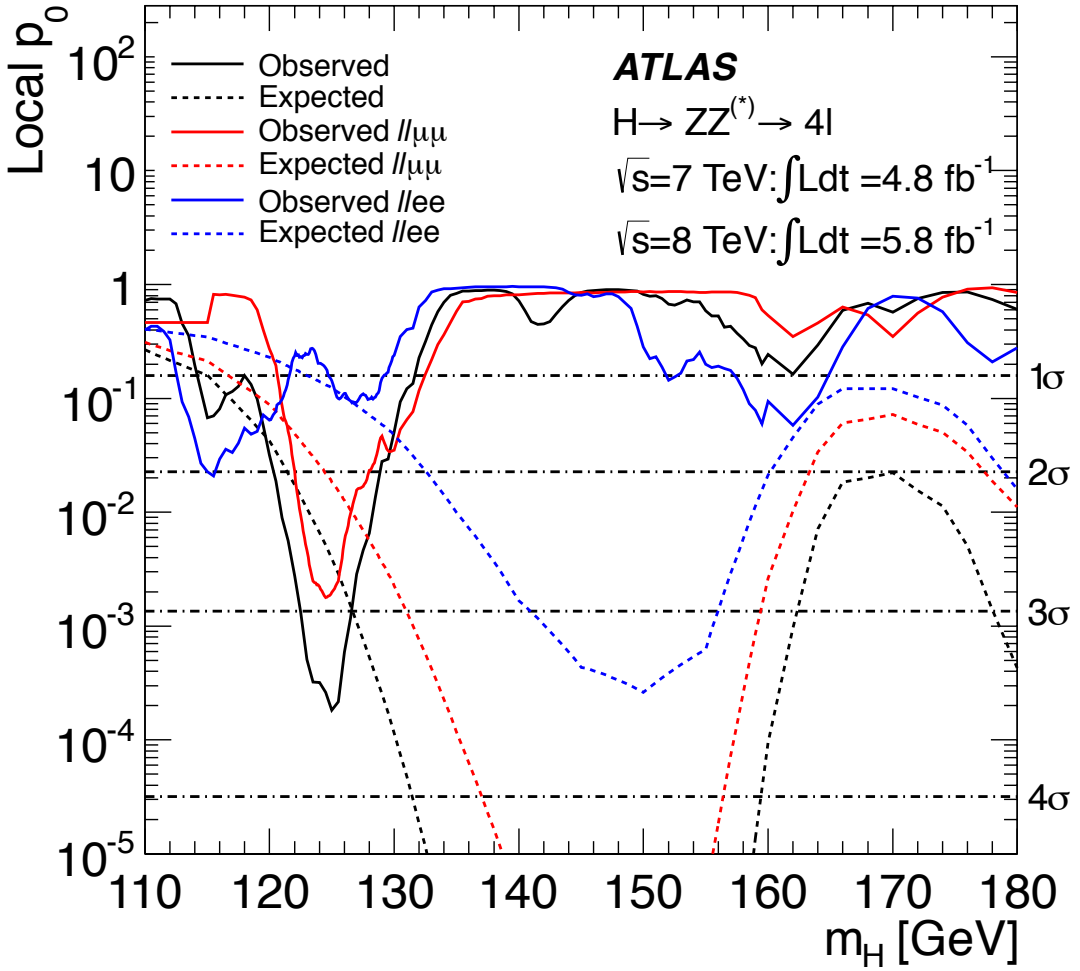




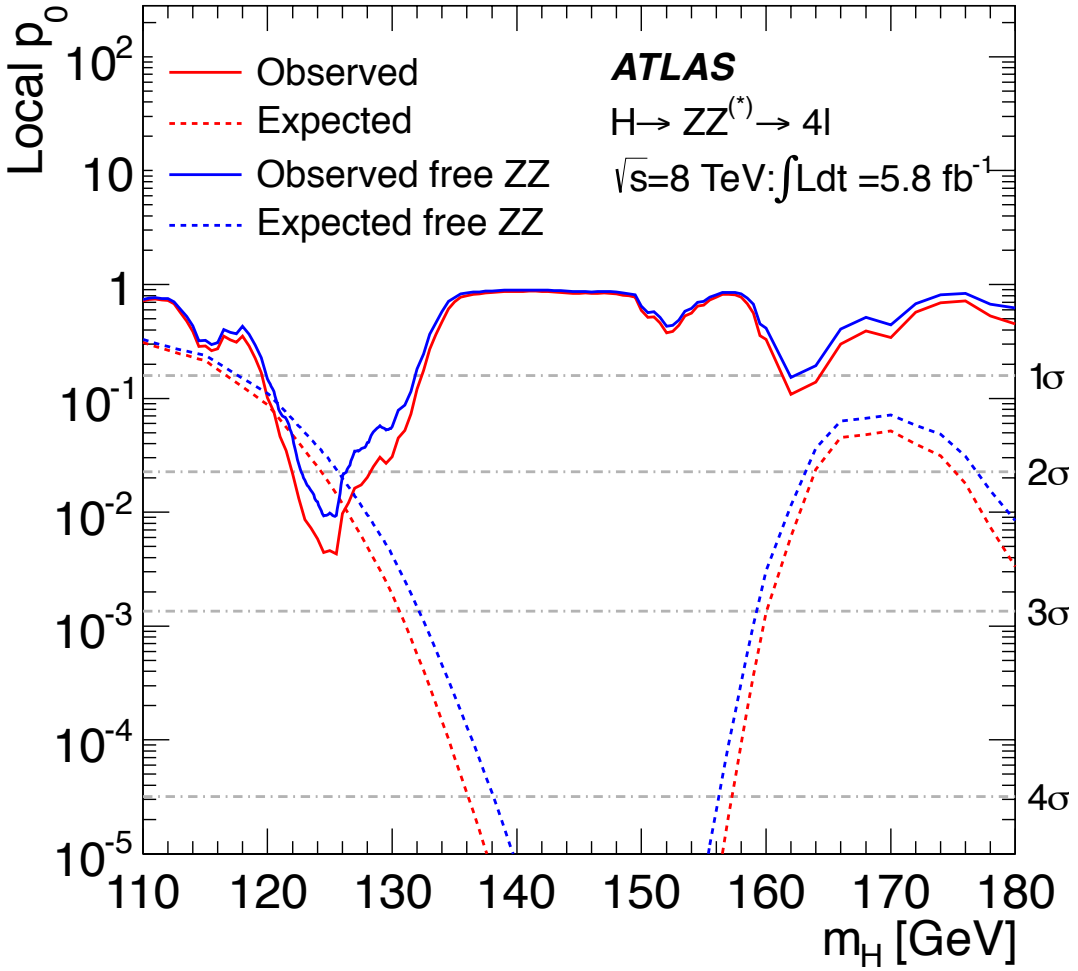




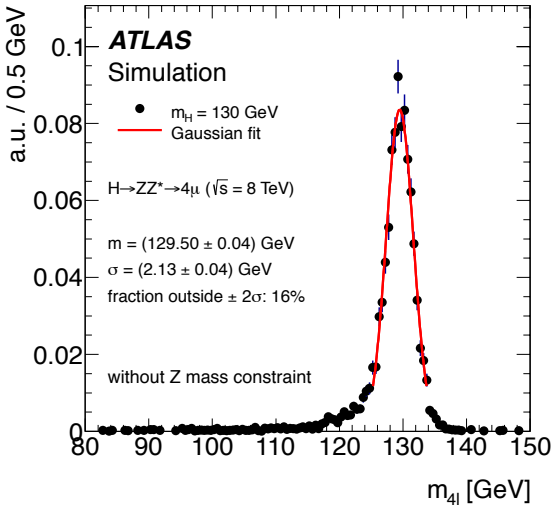
Significance of Excesses by sub leading lepton type

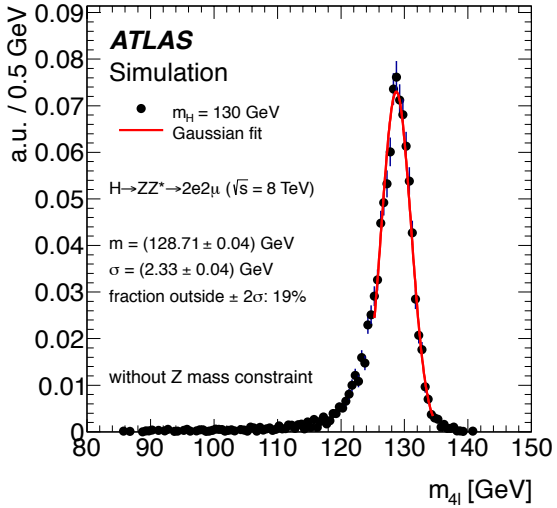


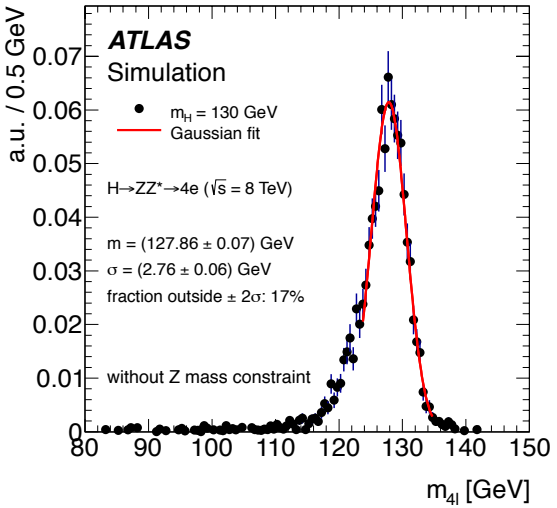
Effect of Background ZZ normalisation

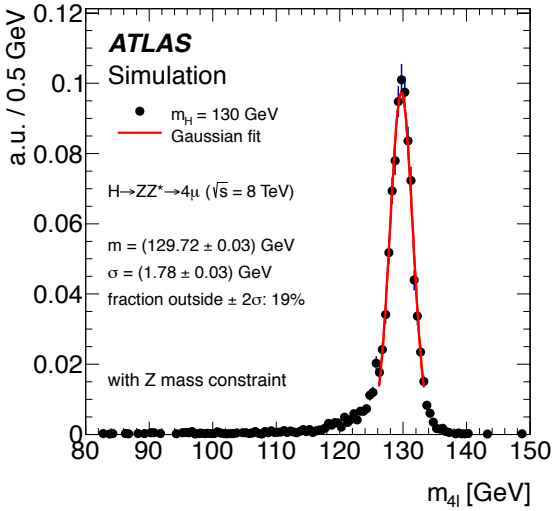


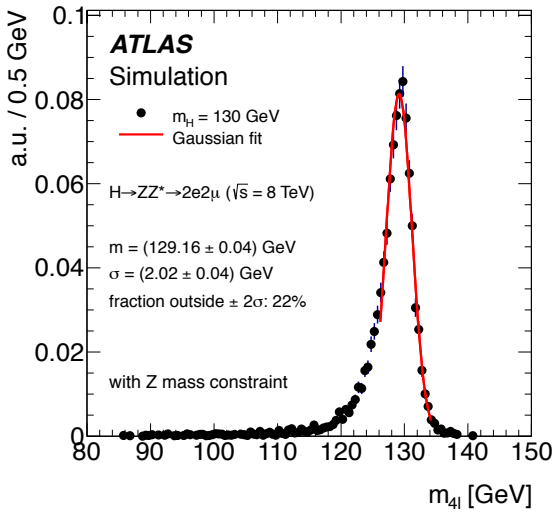
Mass resolution

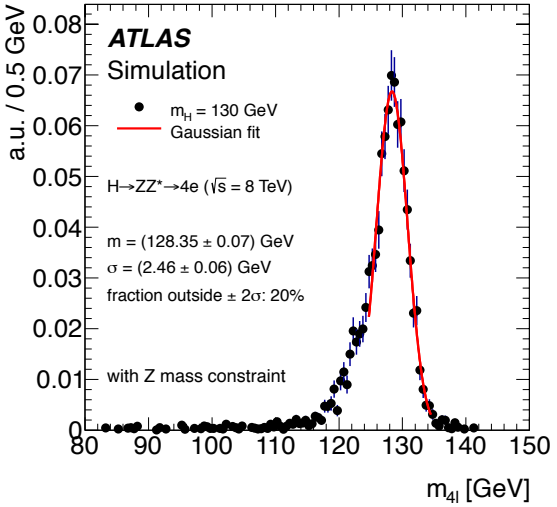










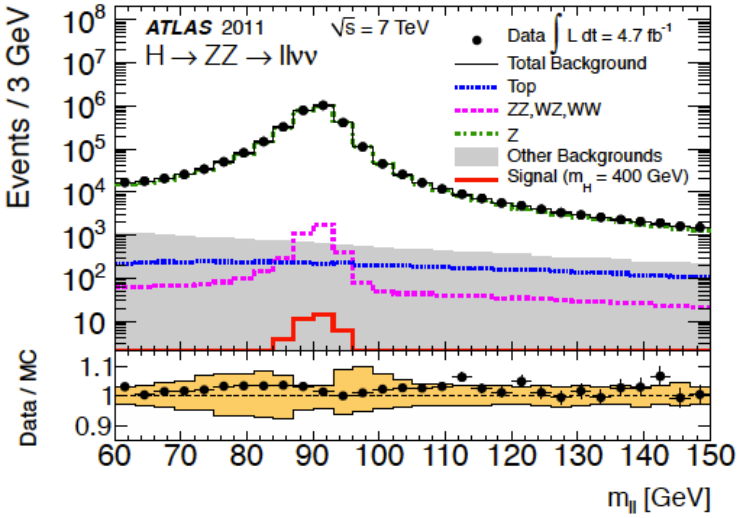


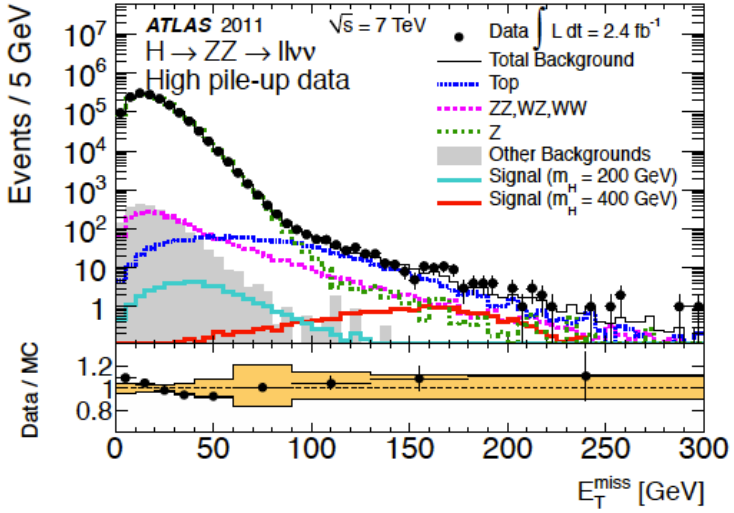
H→ZZ→llνν

- Exactly 2 opposite charged leptons (veto events with a 3rd lepton with p_T > 10 GeV)
- Lepton pair is required to be close to the Z pole $|m_Z - m_{ll}| < 15$ GeV
- Events with b-tagged jets above 20 GeV are rejected
- Backgrounds:
  - Irreducible: Standard Model diboson production
  - Reducible. Suppressed by invariant mass requirement: top, W boson, multijet production
  - Dominant: inclusive Z production (especially for low Higgs masses)
- Optimised selections for two m_H regions:
  - 200 GeV< m_H <280 GeV & 280 GeV< m_H < 600 GeV

low mass	high mass
$E_T^{miss} > 66$ GeV	$E_T^{miss} > 82$ GeV
$1 < \Delta\Phi(\ell,\ell) < 2.64$	$\Delta\Phi(\ell,\ell) < 2.25$
$\Delta\Phi\left(\vec{p}_T^{miss}, \vec{p}_T^{jet}\right) < 1.5$	$\Delta\Phi\left(\vec{p}_T^{miss}, \vec{p}_T^{jet}\right) < 0.5$
	$\Delta\Phi\left(\vec{p}_T^{miss}, \vec{p}_T^{\ell\ell}\right) < 1$

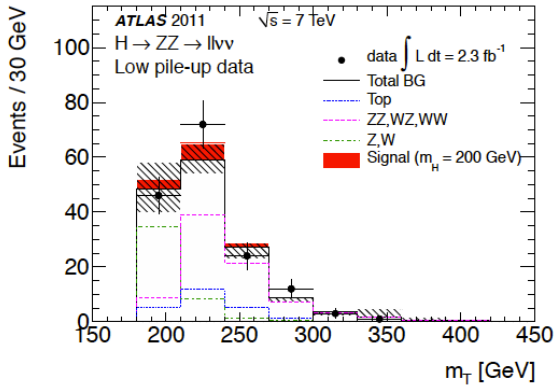
- The data sample was split in two:
  - a low pile-up scenario (in average 6 interactions per bunch crossing)
  - and a high pile-up scenario (in average 15 interactions per bunch crossing)

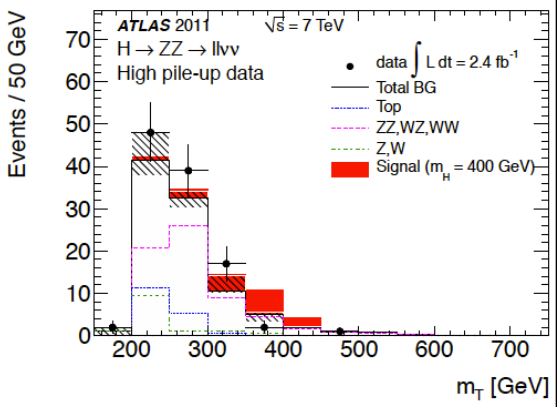




H→ZZ→llνν

- Most BG estimated from MC and verified with data.
  - WZ: verified with three-lepton events
  - Top: verified in two control samples: ($e^{\pm}\mu^{\pm}$), and b-jet + m_{ll} side-band.
  - W + jets: verified with like-sign
  - Z + jets: verified with events rejected by ΔΦ
- No indication of excess
  - $319 < m_H < 558$ GeV excluded at the 95% CL.





$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\,\text{miss}}|^2}\right]^2 - |\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\text{miss}}|^2$$